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## 13. ABSTRACT (Maximum 200 words)

This paper presents the results of three closely related studies on the bending deformation increase of beams made of bending-extension (b-e) coupled fiber-reinforced composites, such as N-layered regular (equal thickness layers) antisymmetric cross-ply laminates. The loadings on the beams are either pure bending (without any strain actuation) or strain actuation induced by the actuators (such as lead zirconium titanate [PZT] drivers) bonded to both or one side of the beam. These represent the simplest loadings experienced by the low-frequency wall-driven projectors, consisting of surface-bonded PZT actuators and radiators made of ceramics, metals, or recently fiber-reinforced composites. The three studies have a direct bearing on developing composite bender bar projectors.

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21a. NAME OF RESPONSIBLE INDIVIDUAL P. Y. Tang	21b. TELEPHONE <i>(include Area Code)</i> (619) 553-1938	21c. OFFICE SYMBOL Code 564

# BENDING DEFORMATION INCREASE OF BENDING-EXTENSION COUPLED COMPOSITE BEAMS BONDED WITH ACTUATOR(S)

Po-Yun Tang  
Advanced Concepts Branch  
NRaD

Naval Command, Control and Ocean Surveillance Center  
San Diego, CA 92152-5001

This paper presents the results of three closely related studies on the bending deformation increase of beams made of bending-extension (b-e) coupled fiber-reinforced composites, such as N-layered regular (equal thickness layers) antisymmetric cross-ply laminates. The loadings on the beams, as depicted by figures 1, 2, and 3, are either pure bending (without any strain actuation) or strain actuation induced by the actuators (such as lead zirconium titanate [PZT] drivers) bonded to both or one side of the beam. These represent the simplest loadings experienced by the low-frequency wall-driven projectors, consisting of surface-bonded PZT actuators and radiators made of ceramics, metals, or recently fiber-reinforced composites. The three studies have a direct bearing on developing composite bender bar projectors.

As is well-known, the basic radiation mechanism of all low-frequency wall-driven transducers, including bender bar projectors, is the conversion of the extensional deformation of the actuator into the bending motion of the radiator material. In light of this, it seems natural and beneficial to look into a radiator material that inherently has the b-e coupling properties. The three studies described above indeed confirm this idea, showing that substantial bending deformation increases can be obtained by use of the b-e coupling properties of two-layered regular antisymmetric cross-ply laminates.

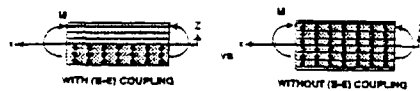
By using the classical laminated plate theory [1], analytical formulas have been obtained for the bending deformations of the b-e coupled and the pertaining homogeneous cross-ply laminated beams under the three studies. These results have then been used to derive the desired formulas for the bending deformation increase of the laminated beams investigated by the three studies. As a check, the deformation formulas obtained for b-e coupled orthotropic composite beams have been reduced to those for homogeneous isotropic beams and shown to be identical to the known results [2].

The numerical results obtained from the derived bending deformation increase formulas are highlighted

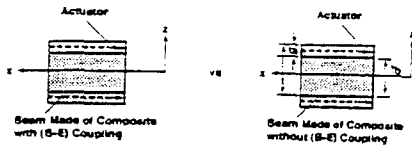
in figure 4 and table 1 for the first study, and in figures 5 and 6, respectively, for the second and third studies. Figure 4 shows the bending deformation increase,  $\alpha$ , due to b-e coupling properties of regular antisymmetric cross-ply laminates under the first study, as a function of the ply stiffness ratio,  $F$ , and the number of layers,  $N$ . In this figure,  $\alpha$  and  $F$ , respectively, are defined as  $\alpha = \kappa/\kappa_{HO}$ , and  $F = E_2/E_1$ , where  $\kappa$  and  $\kappa_{HO}$ , respectively, are middle surface bending curvatures of beams made of composites with and without b-e coupling properties, while  $E_1$  and  $E_2$ , respectively, are ply Young's moduli in the fiber and its transverse directions. As shown in figure 4,  $\alpha$  increases as  $F$  or  $N$  decreases. Theoretically, a maximum value of 4.0 can be achieved for  $\alpha$  when  $F$  approaches zero and  $N=2$ . For the existing two-layered regular antisymmetric cross-ply laminates, as shown in table 1, a maximum value of 2.59 can still be achieved for  $\alpha$  with graphite/epoxy composites. Apparently, there is plenty of room for material improvement to increase  $\alpha$  value for the existing laminates.

Figure 5 shows the bending deformation increase,  $\alpha$ , due to b-e coupling properties of existing (two-layered regular antisymmetric cross-ply) laminates under the second study, as a function of the actuator-beam thickness ratio,  $t_a/t_b$ . Under the strain actuation of the two actuators, the beam is in the state of pure bending. Hence, as shown in figure 5, as the actuator thickness (or  $t_a/t_b$ ) approaches zero, the  $\alpha$  values for various laminates approach their respective  $\alpha$  values listed in table 1 for pure bending (without any strain actuation).

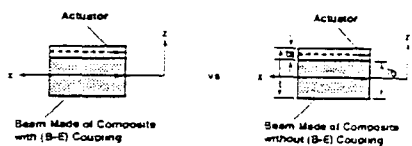
Figure 6 shows the bending deformation increase,  $\alpha$ , due to b-e coupling properties of existing laminates under the third study, as a function of  $t_a/t_b$ . These results are remarkably different from those shown in figures 4 and 5 for the first two studies. These differences are attributed to the differences in the loadings on the beams—the beam under the third study is in the state of combined bending and extension due to the strain actuation of only one actuator, whereas the beams under the first two studies are in the state of pure bending as explained earlier.



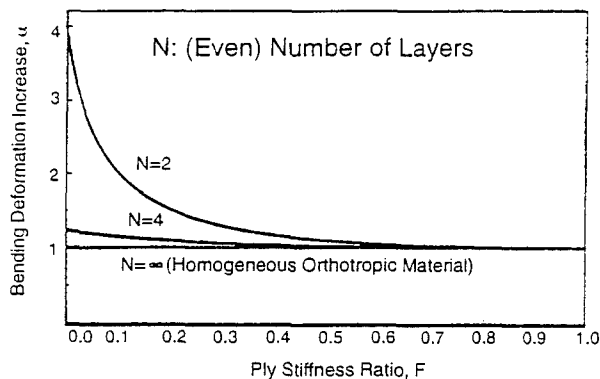
**Figure 1.** First study—pure bending of a composite beam.



**Figure 2.** Second study—induced strain actuation of a composite beam bonded to both sides with the actuators.



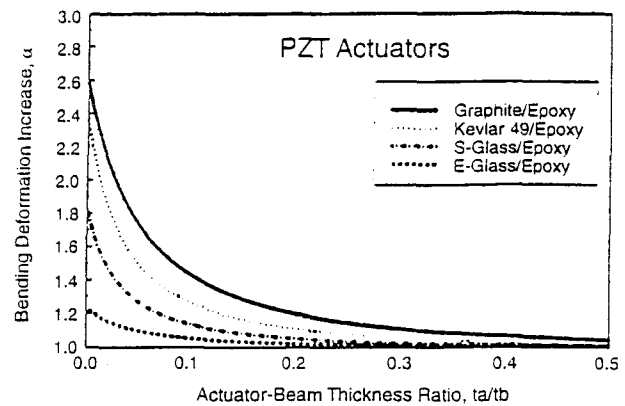
**Figure 3.** Third study—induced strain actuation of a composite beam bonded to one side with the actuator.



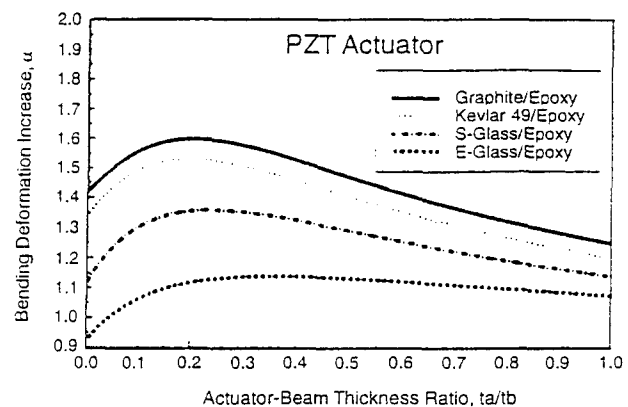
**Figure 4.** Bending deformation increase,  $\alpha$ , due to b-e coupling properties of regular antisymmetric cross-ply laminates.

**Table 1.** Bending deformation increase,  $\alpha$ , predicted for the existing two-layered regular antisymmetric cross-ply laminates.

Composite System	$\alpha$
E-glass/Epoxy	1.23
S-glass/Epoxy	1.83
Kevlar 49/Epoxy	2.38
Graphite/Epoxy	2.59



**Figure 5.** Bending deformation increase due to b-e coupling properties of two-layered regular antisymmetric cross-ply laminates under the second study.



**Figure 6.** Bending deformation increase due to b-e coupling properties of two-layered regular antisymmetric cross-ply laminates under the third study.

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